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CPV Cell Infant Mortality Study

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Abstract. Six hundred and fifty CPV cells were characterized before packaging and then after a four-hour concentrated on-sun exposure. An observed fielded infant mortality failure rate was reproduced and attributed to epoxy die-attach voiding at the corners of the cells. These voids increase the local thermal resistance allowing thermal runaway to occur under normal operation conditions in otherwise defect-free cells. FEM simulations and experiments support this hypothesis. X-ray transmission imaging of the affected assemblies was not found capable of detecting all suspect voids and therefore cannot be considered a reliable screening technique in the case of epoxy die-attach.

Keywords: multi-junction, photovoltaic, thermal runaway, CPV, die-attach, void.
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INTRODUCTION

A 0.5–1% infant mortality failure rate has been observed for some III-V multi-junction cell assemblies [1]. Considering the series connection of cells within a module, a 1% failure rate will have a much larger consequence in terms of power production for the entire module and system. The failures observed for these cell assemblies are characterized by their open circuit voltage dropping instantaneously to zero within the first hours of on-sun exposure and are suspected to be a manifestation of thermal runaway. The goal of the present study is to identify the root cause of this characteristic failure in an effort to define an appropriate screening procedure such that this population of cells may be removed from production.

In a previous set of experiments, it was found that a ~4 area % void located in the solder die-attach at the corner of the cell would precipitate a thermal runaway failure through *both* a prescribed current ramp once ~3.5 A forward bias is achieved, and similarly open circuit conditions while on-sun under high concentration [2]. These failures are similarly characterized by the open circuit voltage dropping instantaneously to zero.

In the current study, 650 bare cells were characterized before assembly and then again following packaging and an on-sun exposure intended to precipitate the infant mortality failure. In an additional effort, a finite element model was created to confirm that voids alone are capable of precipitating thermal runaway.

MATERIALS AND METHODS

Cell Characterization and Exposure

Six hundred and fifty III-V triple-junction (1-cm^2) solar cells were acquired for this study. This population was not previously screened and selected, as would be the case prior to next level assembly. The cells were initially characterized electrically by dark JV response and their electroluminescence images recorded. The cells were then packaged into receivers while maintaining cell traceability. At the receiver level, the cell assemblies consist of an epoxy die-attach and direct-bonded copper (DBC) substrate. Once packaged, a screening of each cell was performed. This screen was to ascertain if any damage had occurred through packaging or shipment and consisted of an application of 10 mA forward bias where EL emission was visually checked and the resulting voltage response recorded. Each receiver was then placed on-sun under 500x concentration for at least four hours with a DNI of 750 W/m^2 or greater. Following exposure, the same 10 mA forward bias screen was performed. Those cells that did not emit and/or demonstrated a significant drop in voltage were considered failures and tagged for subsequent characterization. Each cell suspected of failure was imaged via IR emission at 100 mA forward bias and X-ray transmission. The dark JV response was also repeated and the cell assemblies finally cross-sectioned to optically image the die and die-attach in the suspected area of failure.

Finite Element Modeling

A finite element model of a CPV cell assembly was constructed using COMSOL to simulate the coupled electrical and heat transfer problem of a CPV cell in forward bias. The cell is modeled as a laminate composed of a silver busbar, a germanium cell and a gold back contact, attached with solder or epoxy to a direct-bond copper (DBC) substrate. For simplicity, the busbar covers the entire top surface of the cell. It is shown that this gives a reasonable approximation for the busbar's behavior in forward-bias simulations. The top surface of the busbar is held at electrical ground and a uniform inward current density is applied to the bottom surface of the solder. At the interface between the busbar and the cell, a temperature- and current-dependent voltage drop according to the constitutive equation for a triple-junction cell is enforced:

$$V(J,T) = \frac{n}{q}\left[3kT\ln\left(\frac{J}{CT^3}\right) + \sum_{i=1}^{3} E_{g,i}(T)\right] \qquad (1)$$

where n=1 is the diode ideality factor, q is the charge of an electron, k Boltzmann's constant, C =15 is a fitting constant and E_g is the temperature-dependent bandgap energy expressed in terms of the Varshni Formula for each of the three junctions [2-5]. The remaining surfaces are electrically insulated. The back surface of the substrate is held at a constant temperature, simulating a heat sink. In a typical simulation, the entire assembly starts at the same temperature as the heat sink and current through the cell is ramped up from approximately zero at 0.1 A/cm^2/s. Several sizes of voids are simulated in the die-attach under one corner of the cell and the resulting temperature and local current density at this critical corner is monitored.

RESULTS

The initial dark JV response of a representative sampling of the entire population is presented in Fig. 1. A detailed treatment of all data is beyond the scope of this paper and therefore addressed elsewhere [6, 7]. Of the initial 650 cells three were identified to exhibit the characteristic infant mortality failure: ~2.5 V and 0 V @ 10mA pre- and post-exposure screen, respectively. The initial dark JV responses of these three samples are highlighted in Fig 1 by the bold green (sample (a)), red (sample (b)) and blue (sample (c)) curves. The corresponding initial electroluminescence imagines are presented in Fig 2. Samples (b) and (c) dark JV and EL response are well within the majority of the population which were unaffected by the on-sun exposure.

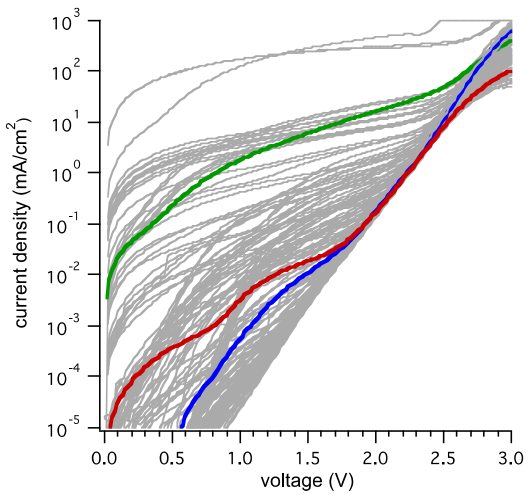

FIGURE 1. Representative sampling of dark JV response of the initially characterized bare cells, with the three infant mortalities highlighted.

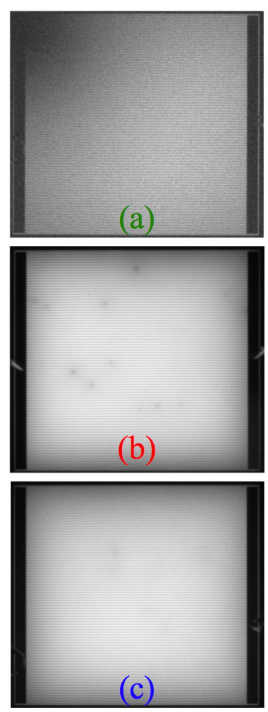

FIGURE 2. EL images of the three infant mortality cells, pre-packaging and exposure.

While sample (a) does exhibit a higher leakage current than the other two failures, it also resides in a portion of the overall population that was otherwise unaffected through exposure.

The IR image of one of the three identified infant mortalities, sample (c), is presented in Fig. 3. The other two identified infant mortalities demonstrate similar IR images that are characteristic of a current shunt that has developed under the corner of the cell. In this case, the hot spot in the IR image is due to Joule heating of the device since all applied current travels through the shunt. X-ray transmission images of two of the three failed cells are presented in Fig. 4.

FIGURE 3. Representative IR image of a failed cell in the infant mortality population.

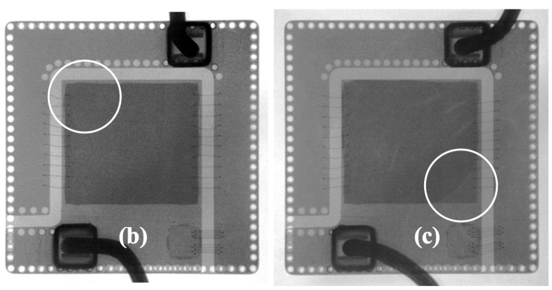

FIGURE 4. X-ray transmission image of two failed cells in the infant mortality population. The locations of epoxy void and cell failure are circled.

A common screening technique, the image of sample (c) shows evidence of a large void in the epoxy die-attach under the lower right corner of the cell while the image of sample (b) does not demonstrate such an obvious artifact in the location of cell failure (circled regions). The corresponding cross-sectional images taken of these samples are presented in Fig. 5 (The cracked and pitted appearance of the cell is an artifact of the polishing process). The lower left of sample (c) (c-L) contains epoxy to the corner of the cell while the lower right corner (c-R), and location of the failure, contains a large void as depicted in the X-ray image, ~ 4.5 area %. Contrary to the negative indication for voids of X-ray image of sample (b), however, a significant epoxy void is also present in its affected corner, ~3.7 area %. Similar to sample (b), sample (a, not presented) did not show evidence of voiding in its X-ray image, though one was present at the failed corner and approximated to be ~3.6 area % through detailed examination of the X-ray and cross-section images.

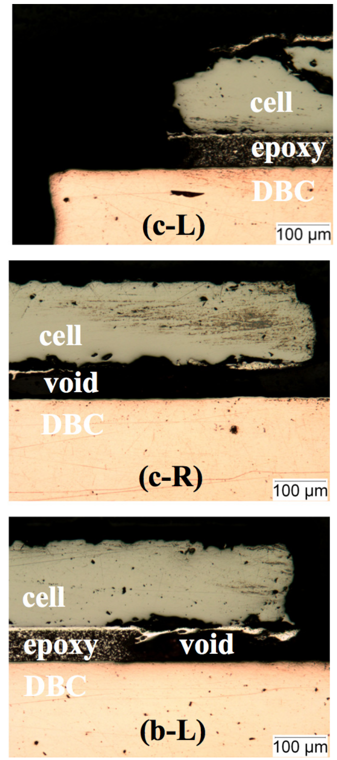

FIGURE 5. Optical micrographs of cross-sectioned infant mortality samples in the corner of failure.

ANALYSIS

From the original population of 650 cells, three characteristic infant mortality failures were identified. This represents less than the 0.5–1% failure rate observed in the field, however, the original population was not screened, as would be the case in production. If a limit of acceptable leakage current were applied, approximately 50 cells would have been excluded thereby increasing the experimental failure rate to field levels.

The characteristic infant mortality failures appear to be a result of a packaging failure (epoxy die-attach void) rather than a pre-existing defect at the bare cell level. It is speculated that the increased thermal resistance due to the epoxy void precipitates thermal runaway in that corner of the cell: a feedback loop of Joule heating and current crowding that ultimately results in the formation of a current shunt rendering the device as an overall short. In order to further confirm this hypothesis, a finite element model was used to simulate thermal runaway in an otherwise defect free CPV cell.

The FEM is first validated by simulating the local current density at the corner of the cell over a solder void of 3, 4 and 5 area % against the applied current, Fig. 6. It is presumed that when the rate of change of the local current density becomes very large, thermal runaway has occurred. This is the case for the 4 area % void at approximately 3.5 A as in good agreement with previous experiments [2].

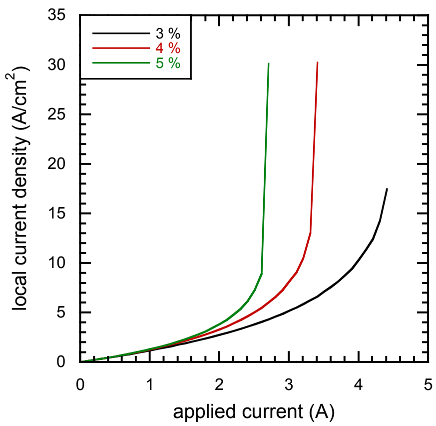

FIGURE 6. FEM simulation of the local current density above a solder void with increasing applied current for three void sizes.

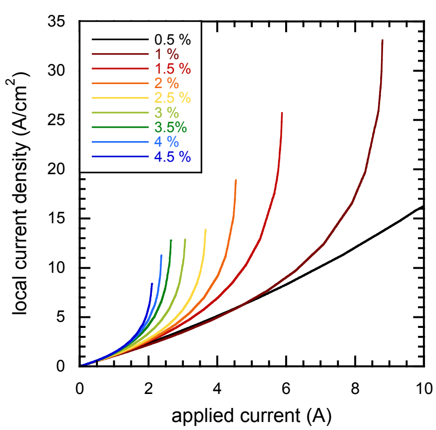

FIGURE 7. FEM simulation of the local current density above an epoxy void with increasing applied current for nine void sizes.

A similar family of curves is produced to simulate the present case of infant mortality failures, Fig. 7. The local current density in the cell above the voided corner is plotted against applied current for a 1-cm^2 cell. If the experimentally determined threshold of an applied current of 3.5 A to precipitate thermal runaway is applied, all voids greater than ~2.5 area % will result in on-sun failure. This result is in good agreement with the three infant mortalities identified in the present study and therefore suggests the voids alone were sufficient to cause failure.

CONCLUSIONS

An infant mortality failure rate observed for some fielded III-V multi-junction cell assemblies has been reproduced for a characterized 650-piece sample set. These characteristic failures could not be correlated with cell defects, but can be explained by thermal runaway at epoxy die-attach voids located at a corner of the CPV cell. These voids create areas of higher thermal resistance that promote thermal runaway in otherwise defect-free cells. This explanation is consistent with both FEM simulation and on-sun experiment. While X-ray imaging of the packaged cells is commonly used to detect these voids, only one of the three packages showed an artifact in its image consistent with a die-attach void. Reduced contrast in imaging the less dense epoxy die-attach, as opposed to solder, may reduce the effectiveness of this screening technique for these assemblies. In light of the FEM simulations, a forward bias current proof test could be applied as a method for evaluating the adequacy of the packaging. Effort should also be aimed toward directly addressing the packaging issue.

ACKNOWLEDGMENTS

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REFERENCES

[1] N. Bosco and S. Kurtz, "Quantifying the Thermal Fatigue of CPV Modules," *AIP Conference Proceedings,* vol. 1277, pp. 225-228, 2010.

[2] N. Bosco and S. Kurtz, "Accelerated Testing and On-Sun Failure of CPV Die-Attach," in *IEEE ASTR*, Denver, CO, 2010.

[3] J. C. C. Fan, "Theoretical temperature dependence of solar cell parameters," *Solar Cells,* vol. 17, pp. 309-315.

[4] B. V. Zeghbroeck, *Principles of Semiconductor Devices*: Available at http://ecee.colorado.edu/~bart/book/, 1997.

[5] S. K. Geoffrey, *et al.*, "Concentrator multijunction solar cell characteristics under variable intensity and temperature," *Progress in Photovoltaics: Research and Applications,* vol. 16, pp. 503-508, 2008.

[6] C. Sweet, *et al.*, "Correlations in Characterisitic Data of Concentrator Photovoltaics," in *NREL PV Module Reliability Workshop*, Golden, CO, 2011.

[7] C. Sweet, *et al.*, *to be submitted.*